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# Coating to Prevent Frost: Less Defrosting - More Energy Efficiency

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## Abstract

*In laboratory tests on standard heat exchangers, novel anti-ice coatings have shown great potential to save energy. In winter, heat exchangers for heat recovery ventilation (HRV) and heat pumps accumulate ice and require periodic defrosting. The applied organic-inorganic hybrid coatings increased the uptime between two energy-consuming defrosting cycles by a factor of about 2.3. Freezing (ice nucleation) is not inhibited, but the spreading of frost, which originates from ice-nucleation sites, was inhibited. Herein, we outline the work principle and provide quantitative results.*

**Keywords - anti-ice; frost; heat recovery ventilation; HRV; coating**

## 1. Introduction

Specific icing problems of heating, ventilation and refrigeration components have been motivation for the present work. Air-to-refrigerant heat exchangers ('air coils', 'finned tube coils') are applied in refrigeration (for example supermarket display cabinets) or in heat pumps using outside air as heat source. In a refrigerated display cabinet at about +2°C, the fin temperature would typically be about -10°C. In heat pumps, the fins are typically cooled below 0°C when the outside temperature is below about +7°C. Counter-flow air-to-air plate heat exchangers are applied in heat recovery ventilation (HRV). At outside temperatures below typically about -3°C, the more humid outgoing air is cooled by the incoming air to temperatures below 0°C.

In all described applications, frost accumulates on the respective surfaces, acting as barrier, increasing the pressure drop of the fan-driven airflow, and acting as insulation, reducing the heat transfer. Thus, periodical

removal of the frost by melting is necessary, often involving electric heating and/or a period the heat exchanger is out of service. Further devices, including wind turbine wings, apply periodic defrosting.

Common defrosting strategies involve energy, usually heating. An attractive approach is thus to design 'icephobic' surfaces.<sup>[1],[2]</sup> Current knowledge indicates that hydrophobic and superhydrophobic surfaces potentially delay freezing and reduce ice-adhesion.<sup>[3],[4]</sup> However, the efficiency of these surfaces under conditions of high humidity, airflow or icing/deicing cycles has been critically questioned.<sup>[1],[5],[6]</sup>

Especially superhydrophobic surfaces, characterized by extraordinary water-repellency attributed to air pockets between water and the textured substrate surface ('Lotus effect', Cassie-Baxter state), have shown that when exposed to condensation, water possibly condenses inside the surface texture, voids the 'air-pocket-state' and increases ice adhesion due to a larger contact area compared to a smooth surface. To date, none of the proposed superhydrophobic anti-ice surfaces has been reported to exhibit a sustained Cassie-Baxter state during condensation.<sup>[7],[8]</sup>

Besides discussing the practical application of freeze delay as sole anti-ice strategy, we investigate a novel concept for technical anti-ice coatings suitable for devices applying periodic defrosting. We take into account, that freezing is not completely avoided, but occurs on single spots. A surface that effectively inhibits frost spreading should thus readily extend the cycles between defrosting intervals and reduce energy consumption.

## **2. Methods**

### **2.1. Materials**

A standard aluminum surface was compared with aluminum coated with coatings A1, A2 or B1. All three coatings are organic-inorganic hybrid coatings. A1 and B1 were previously published;<sup>[9],[10]</sup> A2 is a further development to reduce the curing temperature from 200°C to 60°C. All coatings are applied as wet coatings by spraying or dipping and cure to form 2-5 µm thick films with a smooth, hydrophobic surface. The surfaces provide no micro- or nanotexture and thus no superhydrophobicity. Coatings A1 and B1 are identical except that coating A1 additionally comprises a reactive silicone (polydimethylsiloxane, PDMS) additive. A2 comprises a similar PDMS additive. A part of the PDMS additive moves during curing towards the surface; thus, A1 and A2 provide an improved hydrophobic surface that basically consists of PDMS. The PDMS additive is chemically bond to the coating matrix and not leached out.

Water contact angles of the surfaces were determined with a DSA 10 from Krüss. All results are based on at least five measurements, standard deviation is between 1° and 3°.

## 2.2. Ice test chamber

To investigate freeze delay and frost spreading, we constructed an ice test chamber. It comprises a test box (Fig. 1, the sample plate is mounted into the left wall) equipped with a cooling element and sensors to keep  $+12^{\circ}\text{C}$  air temperature and about 90% relative humidity throughout the test runs. The sample plates (101 x 152 mm) are controlled by a separate cooling block (Cu-block with peltier element and thermocouple, see Fig. 2. In Fig. 1 eclipsed by the sample plate). Provided surface temperatures are cooling block temperatures.

At the start of each experiment, the cooling block is placed outside the test box and covered with a thin water film. The sample plates are with their backside placed on the cooling block and attached by freezing at about  $-1$  to  $-3^{\circ}\text{C}$ , which usually does not cause freezing on the front side. The cooling block with the sample plate is mounted into an opening in the wall of the test box with the sample plate in vertical position, facing the test box. The edge of the cooling block consists of a plastic insulation ring and an outer aluminum ring with a heating wire. Throughout the whole experiment, the heating wire keeps the edges of the sample plate above  $0^{\circ}\text{C}$  to prevent contact-freezing from the backside.

The inner area of the sample plates between lines 12 mm from the edges ( $\sim 100\text{ cm}^2$ ) corresponds to the cooling block temperature, which we confirm after each test run by maintaining the ice-covered plates at  $-0.5^{\circ}\text{C}$  for 15 min, where the central area has to stay completely frozen, see Fig. 2 right. Subsequent heating to  $+0.2^{\circ}\text{C}$  has to lead to complete melting. Thus, we expect a maximum error of  $0.5^{\circ}\text{C}$  for the central sample surface. A camera inside the test box continuously monitors the sample plate.



Fig. 1: Ice test chamber

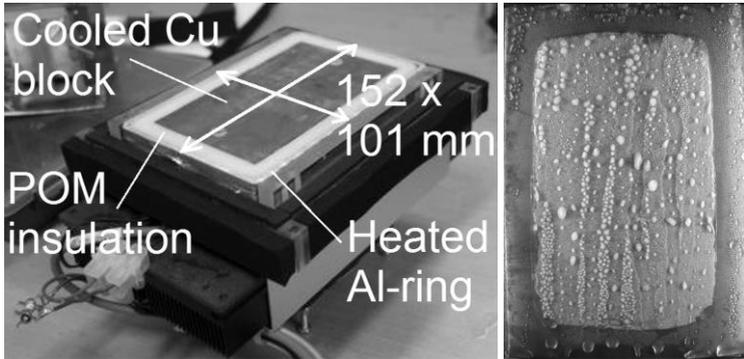


Fig. 2 (left): Cooling block for the sample plate.  
 Fig. 3 (right): Al-plate held 15 min at  $-0.5^{\circ}\text{C}$

All experiments started only after the sample plates had been hold at  $-2^{\circ}\text{C}$  until enough water had condensed to run down in drops ( $\sim 1\text{-}2$  h). Water continuously condenses and drops run down throughout the entire experiments.

### 2.3. HRV performance test

We conducted a HRV performance test with monitoring according to EN 308 with aluminum plate heat exchangers (GS 35 by Klingenburg,  $\sim 50 \times 50 \times 30$  cm, similar heat exchangers are shown in Fig. 4). The tests started with a dry heat exchanger. Temperatures, mass flow, humidity and pressure drop were precisely measured and logged. There is a certain fluctuation, the average conditions (both with and without coating A2) were: Air stream simulating the air going into the building: Inlet: T:  $-11^{\circ}\text{C}$ , flow rate: 680 kg/h, relative humidity: 85%. Outlet: T:  $+6^{\circ}\text{C}$ . Air stream simulation the air coming from the building: Inlet: T:  $+14^{\circ}\text{C}$ , flow rate: 660 kg/h, relative humidity: 40%. Outlet: T:  $-5^{\circ}\text{C}$ , rel. hum.  $>100\%$  (icing is at this outlet).



Fig. 4: Two HRV plate heat exchangers

### **3. Results and discussion**

#### **3.1. Freeze delay**

Ice is the thermodynamically stable phase at temperatures below 0°C. However, liquid water does not instantly freeze. There is solely a certain probability for freezing. The lower the temperature, the higher the probability. It is by random, at which moment freezing actually occurs; the probability can solely be measured with statistical experiments. The onset of ice nucleation for pure bulk water is only at about -40°C.<sup>[11]</sup> Contact with a solid surface will not further inhibit freezing, but rather promote ice crystallization. Thus, the best freeze delay surface should have the lowest possible effect to promote ice nucleation. However, any surface might comprise defects or dirt particles that promote ice nucleation stronger than the average surface and thus might nullify any attempted effect on freeze delay

Bare aluminum leads readily to a significant freeze delay. In a DSC (differential scanning calorimetry) device, we maintained single water drops in aluminum crucibles in liquid state for 1 h even at a temperature down to -20°C. In this DSC test, the water/aluminum interface has an area of about 3 mm<sup>2</sup>. When applying the ice test chamber described above, we did never observe liquid water at temperatures below -12°C. In eight isothermal test runs with different, wet aluminum plates at -7°C, the longest observed freeze delay was 11 h, while in other test runs, freezing occurred already before test start, while cooling down to -7°C. The cooled surface of the plates of about 100 cm<sup>2</sup> is 3000 times larger than the water/aluminum interface in the DSC test. Statistically, this equals repeating the DSC test 3000 times and selecting the lowest observed freeze delay. In addition to the statistic component of the freeze delay as such, the result might also be caused by the larger surface providing a higher probability for freeze-promoting defects or dirt. On real heat exchangers with an even larger surface area of 1 to 500 m<sup>2</sup>, usually no significant freeze delay is observed.

The DSC test and the test in the ice test chamber were repeated with aluminum coated with the hydrophobic coating A1. Within the limited number of tests, no significant difference in the freeze delay as compared to bare aluminum was observed. We do not question, that different surfaces should provide a different freezing probability. However, as the results and considerations above show, the application of a freeze-delay surface as a sole anti-ice measure on a real heat exchanger is not very promising due to the large surface area.

#### **3.2. Frost spreading**

After the first ice nucleation (=freezing) has occurred on a single spot, the hydrophobic coatings behave different as bare aluminum. On bare aluminum, the whole surface freezes almost instantly. Metal surfaces can

provide a continuous water film, despite water contact angles above  $0^\circ$ .<sup>[12]</sup> Such film might explain the extraordinarily fast frost spreading. On the investigated hydrophobic coatings, the spreading of frost over the surface is decelerated. Liquid water continues to condense and eventually run down as drops even in the proximity of frost. To investigate this phenomenon, we placed ice crystals in the center of  $-4^\circ\text{C}$  cold, wet plates and investigated the frost spreading rate. Over the first 30 min, the frost spreading rate, determined as the growth rate of the radius of a circle with an identical area than the actual frozen area, is practically constant. The results are shown in Table 1 and illustrated by Fig. 5, Fig. 6 and Fig. 7. (Further details have been published.<sup>[13],[14]</sup>)

Table 1: Evaluation of water contact angles,  $d_{\text{crit}}$ , and frost spreading rate at  $-4^\circ\text{C}$ . The rate for Coating A1 is based on four, the other rates on one test run

Surface	Water contact angles		$d_{\text{crit}}$ (calculated <sup>[17]</sup> )	Frost spreading rate
	adv.	rec.		
Bare aluminum	$96^\circ$	$50^\circ$	4.2 mm	3000 $\mu\text{m/s}$
Coating A1	$106^\circ$	$96^\circ$	1.8 mm	$2\pm 1 \mu\text{m/s}$
Coating A2	$104^\circ$	$95^\circ$	1.8 mm	2 $\mu\text{m/s}$
Coating B1	$90^\circ$	$70^\circ$	2.8 mm	21 $\mu\text{m/s}$

According to previous investigations, frost spreads from a frozen drop to a neighboring liquid drop.<sup>[15],[16],[17]</sup> Water condenses faster on the frozen drop than on the liquid drop due to the lower vapor pressure of ice as compared to liquid water at the same temperature. The frozen drop growth along the cold surface and finally touches a liquid drop. Due to the different vapor pressure, neighboring liquid drops may even evaporate and contract.

A connection with the critical diameter  $d_{\text{crit}}$ , which is the diameter that a growing water drop has to reach to be large enough to start sliding down a vertical surface, was proposed. The smaller  $d_{\text{crit}}$ , the slower the frost spreading, though no equation for the exact relation between  $d_{\text{crit}}$  and the frost growth rate was established.  $d_{\text{crit}}$  can be calculated from advancing and receding contact angles according to a previously published formula.<sup>[17]</sup> Simplified, the optimal surface should provide low contact angle hysteresis (CAH), which is the difference between advancing and receding contact angles. For a given CAH, the absolute contact angle values should be high. This requires also the receding contact angle to be high. The performance against frost spreading cannot be predicted from static contact angles.

Our results as shown in Table 1, obtained on a larger surface than previously reported tests, support the proposed trend. For the first time, we investigated with B1 a surface with limited hydrophobicity, providing thus a limited deceleration of frost spreading. In principle, any hydrophobic surface with reasonably low CAH should be effective. In a screening test, further coatings, hydrophobic bulk polymers (fluoropolymers, silicone rubber) or

hydrophobic monolayers prepared from perfluoroalkylsilanes performed well, though not as good than coatings A1 and A2.



Frost spreading on wet surfaces at  $-4^{\circ}\text{C}$ . Freezing was initiated in the center of each of the four plates at  $t = 0$ . Opaque drops/areas (after 1 min) or white areas (after 20–45 min) indicate frozen areas.

Fig. 5 (up left): Bare aluminum after 1 min.

Fig. 6 (up right): Coating A1 after 45 min.

Fig. 7 (down left): Coating B1 after 45 min.

Fig. 8 (down right): Coating A1 after 20 min with a forced upward airflow of 1 m/s.

(Fig. 5 to Fig. 7 resulted from tests without forced airflow)

Repeating the frost spreading experiment with an airflow of 1 m/s, which is in the order of magnitude for HRV applications, leads to a significant draw back. Frost spreads fast in the direction of the flow (see Fig. 8), while spreading is still decelerated in the other directions. Even though condensation happens all over the complete surfaces, humidity, and thus also the condensation rate, is highest where the ventilated air meets the cold plate and decreases in the airflow direction. The frost-spreading model presented above suggests growth into the direction of the humidity, which would be in opposite direction of the flow, and does not explain the observed phenomenon. At present, the authors propose that the transport of loose frost by the airflow is the only plausible explanation.

### 3.3. HRV performance test

In a HRV performance test, we compared a bare aluminum heat exchanger with a heat exchanger coated with coating A2. For both test runs, humidity, flow, and air temperatures were practically identical. Thus, the heat transfer for both units is about the same. There is no measurable draw back of the coating on heat conductivity or condensation rate.

Frost accretion over time increases the pressure drop. In a typical HRV installation, defrosting would start at about 130% of the initial pressure drop. The present tests were run until 400% of the initial pressure drop were reached. As shown by Fig. 9, despite the consequences of the airflow discussed above, coating A2 increased the time between defrosting by a factor of 2.3. While frost builds up inside the channels of the uncoated heat exchanger (Fig. 10 left), many channels of the coated heat exchanger are ice-free. Liquid water leaves the channels of the coated heat exchanger, eventually forming icicles (Fig. 10 right). The icicles do not block the flow to the same extend as the frost inside the channels of the heat exchanger.

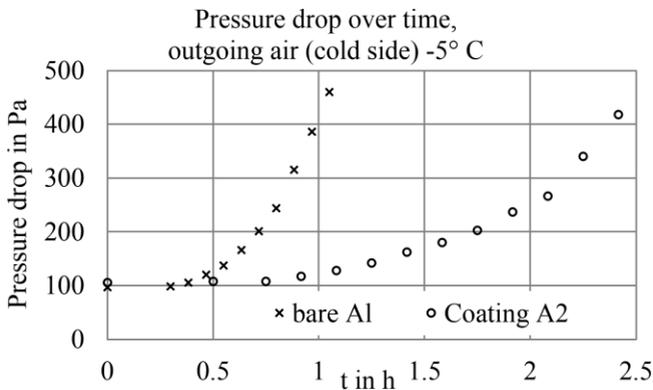


Fig. 9: HRV performance test showing the pressure drop over time



Fig. 10: HRV performance test. Left: Uncoated heat exchanger. Right: Coating A2

#### 4. Conclusion

Decelerated frost spreading is a relevant anti-ice concept for applications that are periodically defrosted, such as, for example, refrigeration, heat pumps, heat recovery ventilation or wind turbines. Common technical hydrophobic surface are readily effective. Amongst these, organic-inorganic hybrid coatings comprising PDMS have proven to be especially suitable.

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